Challenges for Precision Shape Measurements

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Precision Astronomy with Fully Depleted CCDs
Brookhaven National Lab

Measuring Shapes

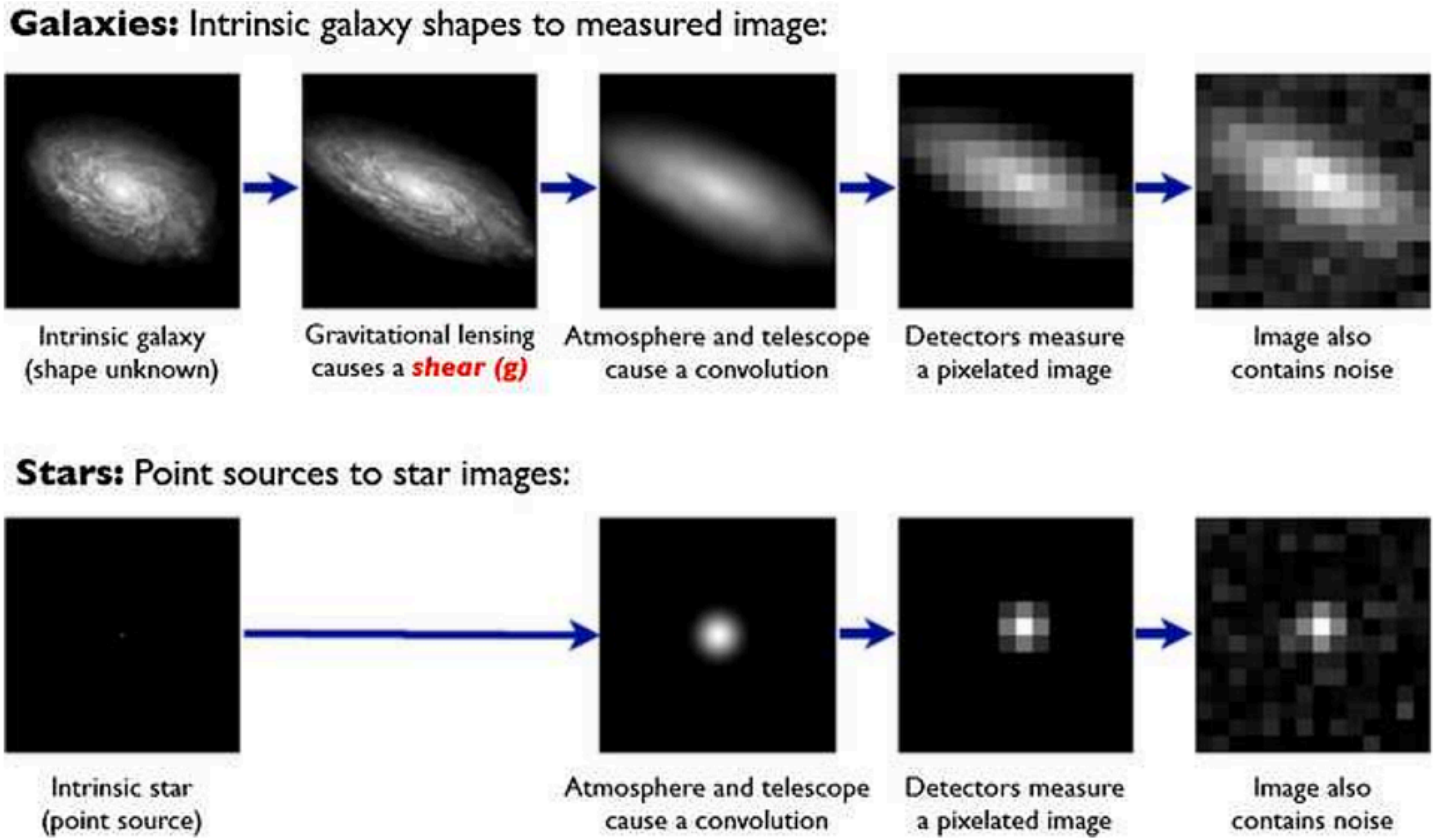


Image credit: Bridle, et al, 2009

Measuring Shapes

This talk

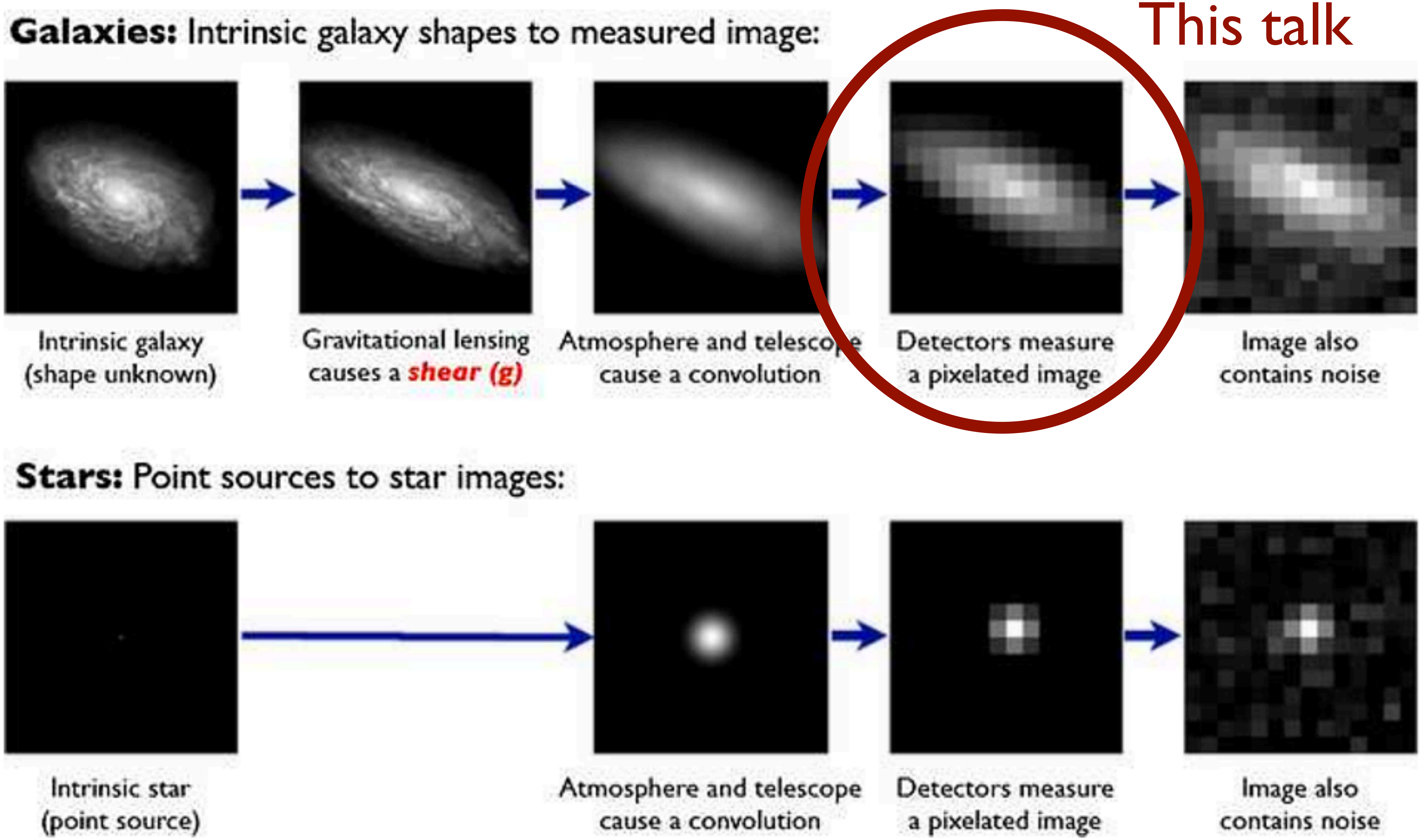


Image credit: Bridle, et al, 2009

Measuring Shapes

Required accuracy for Stage IV missions:

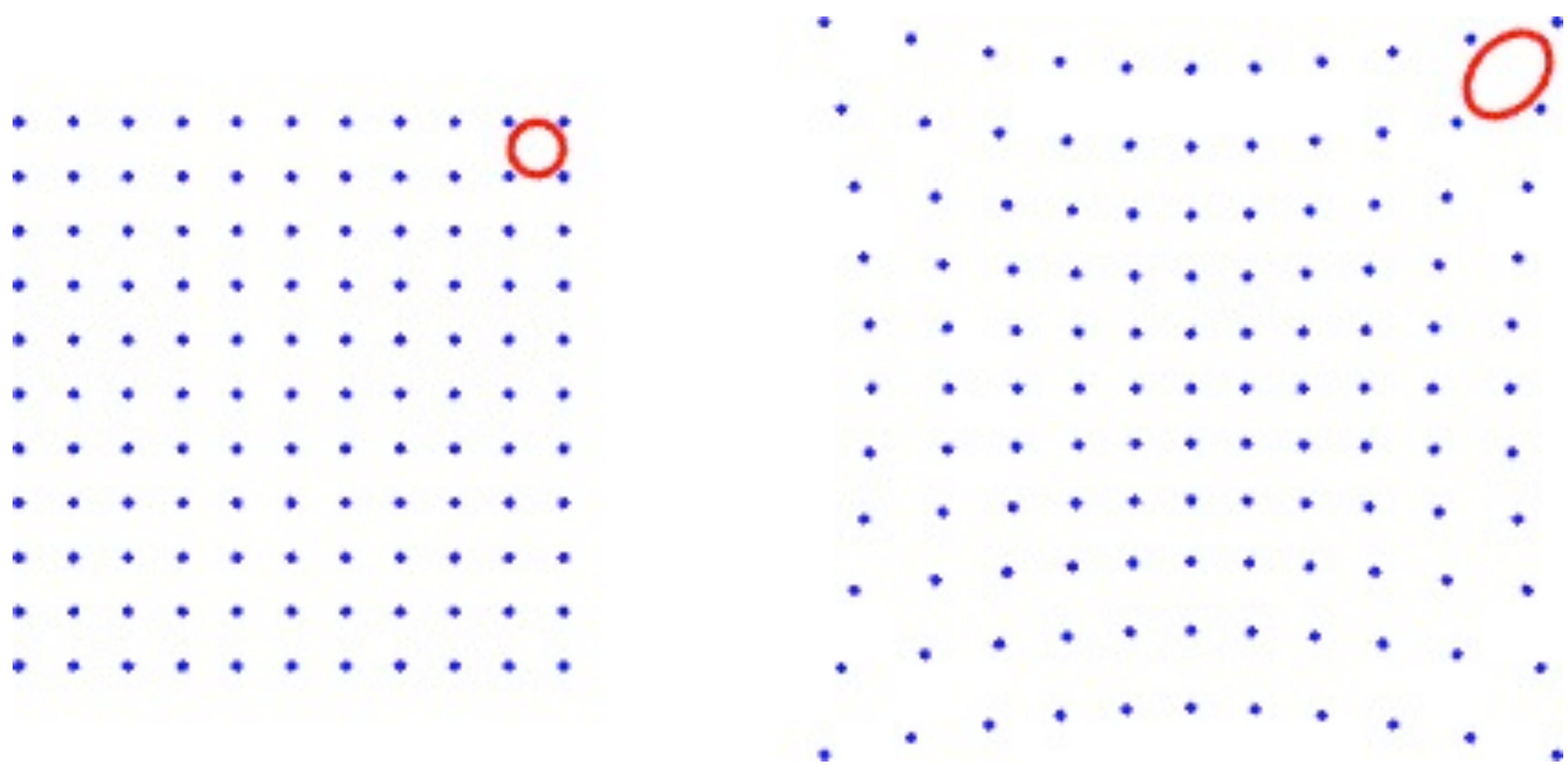
$$g^{obs} = g^{true} + mg^{true} + c$$

$$m < 2 \times 10^{-3}$$

$$c < 2 \times 10^{-4}$$

WCS Effects

The World Coordinate System defines the conversion from chip coordinates to local sky coordinates:



WCS Effects

In general, the transformation includes magnification, shear, and rotation.

$$u = u(x, y)$$

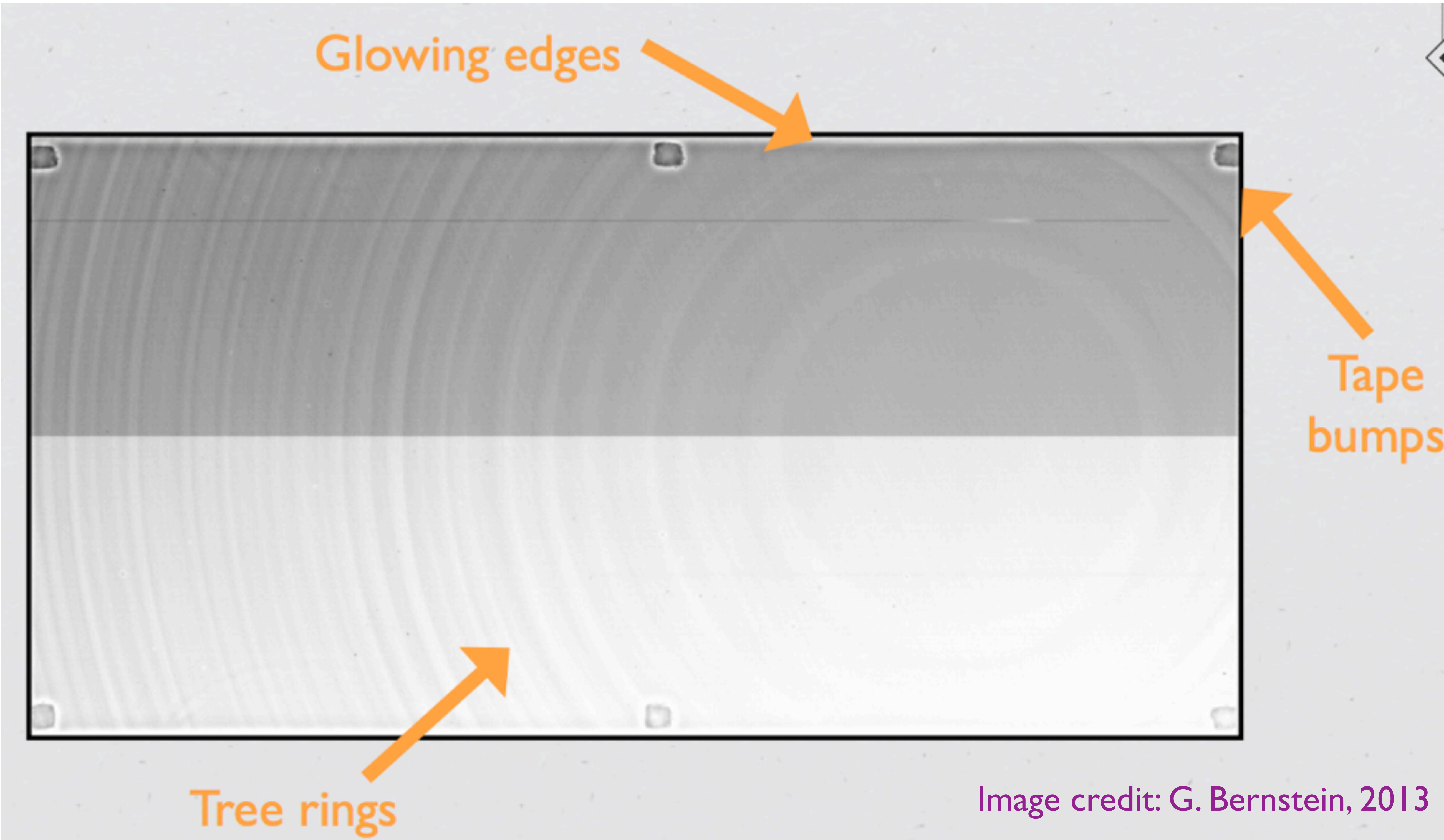
$$v = v(x, y)$$

$$J = \begin{pmatrix} \frac{du}{dx} & \frac{du}{dy} \\ \frac{dv}{dx} & \frac{dv}{dy} \end{pmatrix} = \frac{1+\mu}{\sqrt{1-g^2}} \begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

WCS Effects

- Telescope distortion
- Field rotation
- Differential refraction
- Glowing edges
- Tree rings
- Tape bumps

WCS Effects


Glowing edges
Tape bumps
Tree rings
Image credit: G. Bernstein, 2013

WCS Effects

The impact on shapes:

- Both PSF and galaxy have an additional shear from the shear term in the WCS Jacobian.
- This is a c-type systematic, so need to remove it to better than 2e-4.
- Distortion and convolution do not commute, so cannot subsume the distortion into the effective PSF.

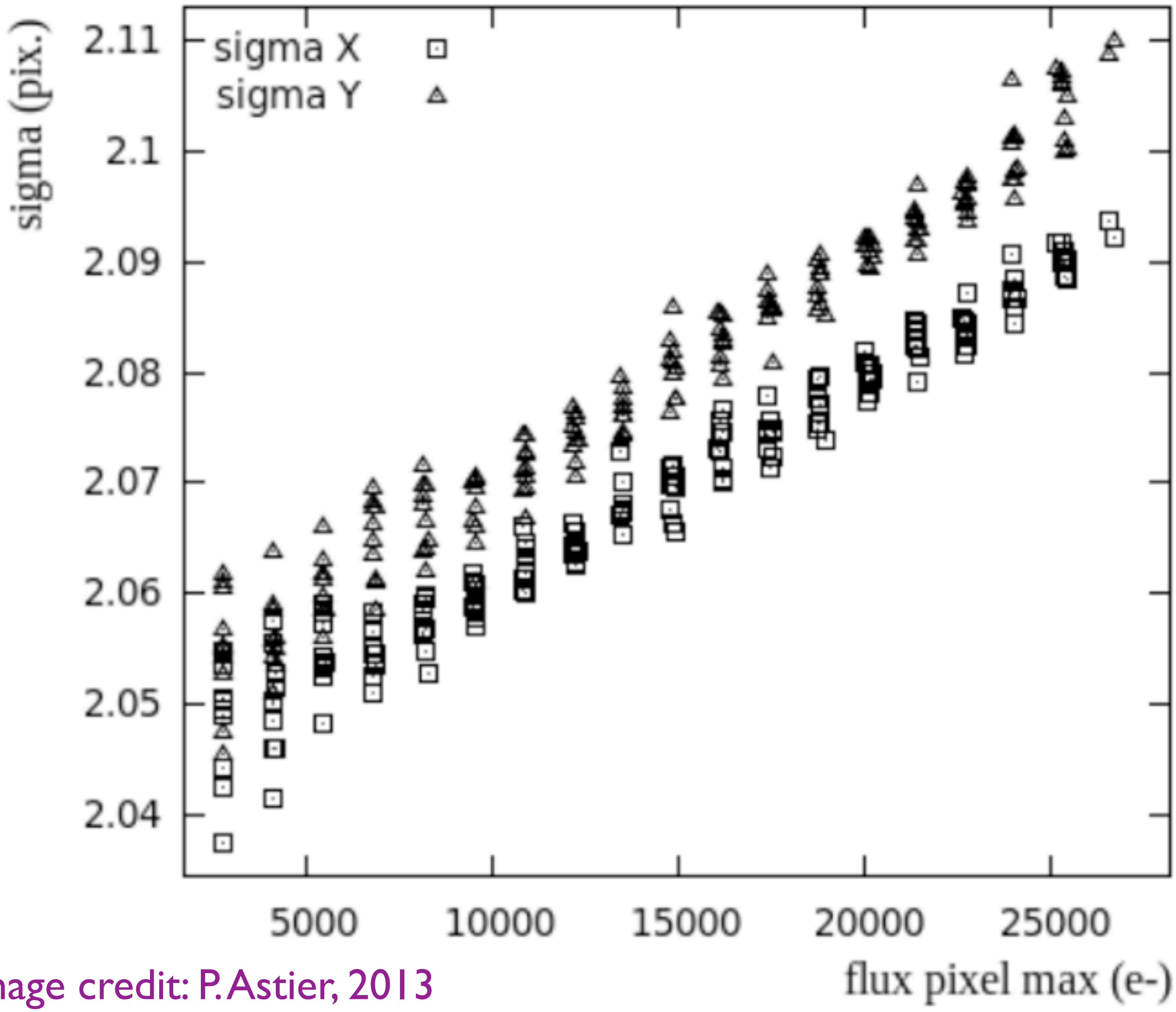
WCS Effects

Solution:

- Determine $u(x,y)$ and $v(x,y)$ from astrometric solutions.
    - c.f. Andres Plazas's talk tomorrow.
- Build PSF and galaxy models in (u,v) coordinates.
- Constrain models using observations in (x,y) coordinates.
- Probably just excise weird stuff like tape bumps from the data.

- Note: if the Jacobian J can be treated as constant over the size of the galaxy, then it is still possible to use an FFT for the convolution.

Brighter-fatter Relation



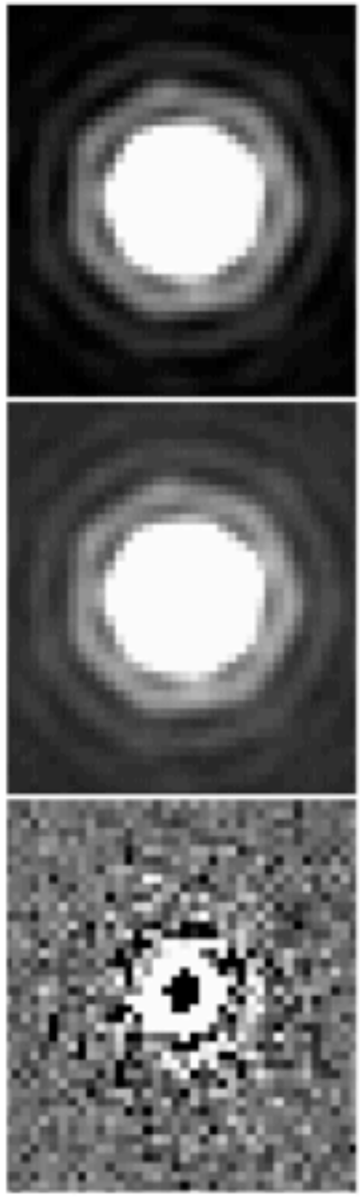


Image credit: P. Astier, 2013

Brighter-fatter Relation

"Tentative" Model:

- Charge builds up in 0,0
- Repels some electrons
- Effectively pulls pixel boundary inward
- δ_{ij} is a function of the charge in the two pixels

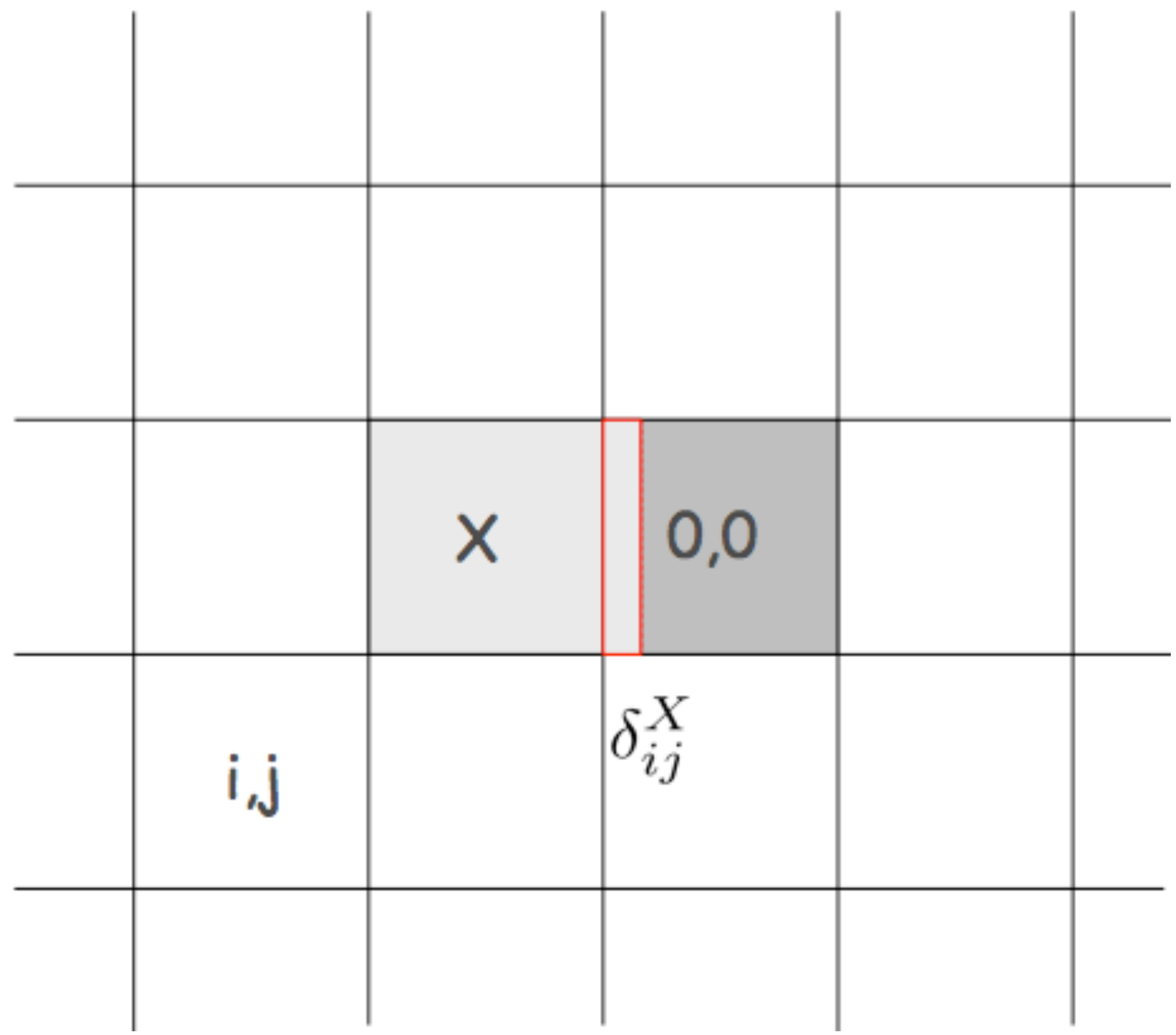


Image credit: P. Astier, 2013

Brighter-fatter Relation

The impact on shapes:

- We usually like to estimate our PSFs from bright stars, S/N > 50-100.
- Most galaxies are fainter. S/N ~ 20.
- PSF used for deconvolution is systematically wrong.
- Mostly an m-type systematic from error in dilution correction.
- Worse: Effect is not really magnitude dependent, it is pixel-flux dependent.
- So cannot simply interpolate PSF in (u,v,m) and use the same magnitude as the galaxy!

Brighter-fatter Relation

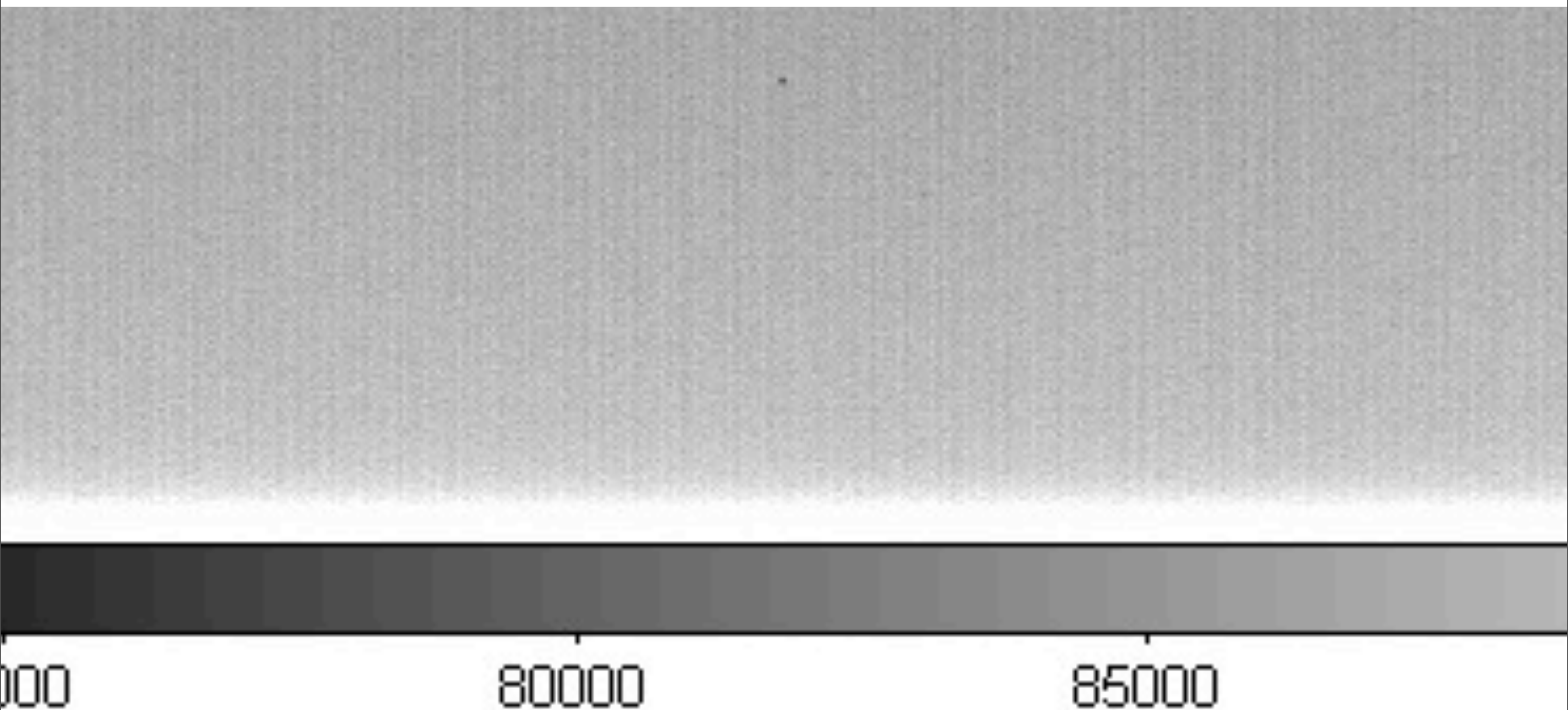
Solution:

- Estimate coefficients from flat field covariances.
    - c.f. Pierre Astier's talk tomorrow.
- Use these coefficients and observed pixel fluxes to reverse the effect in the image.
- Essentially move the charge back to where it "should" have landed.
- Then stars and galaxies all have the same effective PSF.
- This introduces noise correlations, so probably also want to add correlated noise to image to whiten it.

Variable Pixel Size

Repeating Pixel Mask

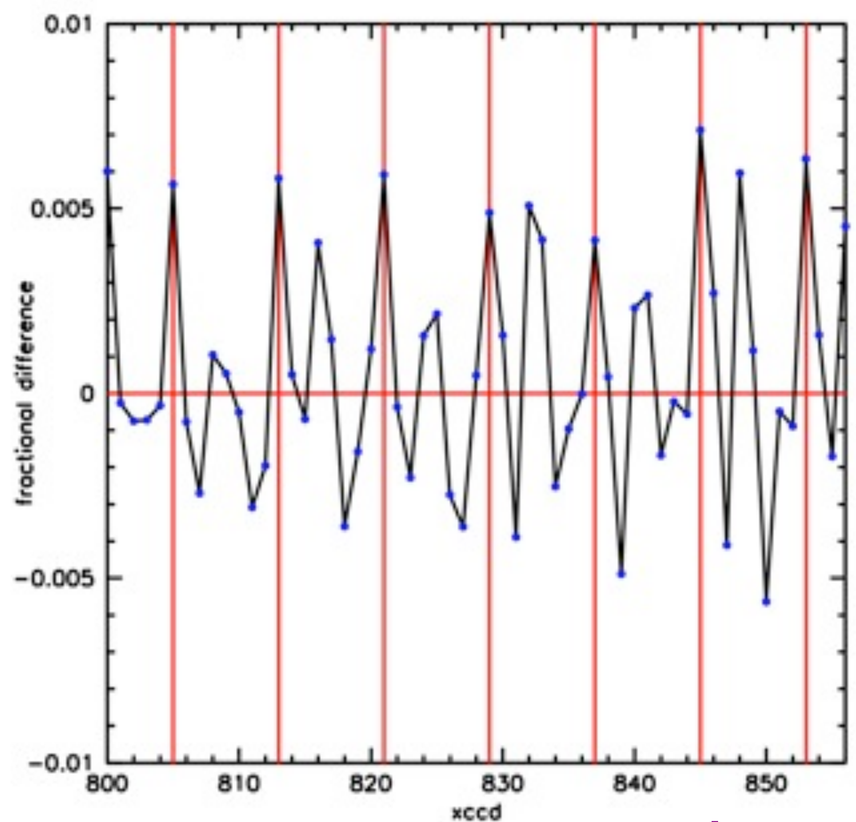
Image credit: T. Diehl, 2008



Variable Pixel Size

Repeating Pixel Mask on DECam

- Cut across columns shows 8 pixel structure at ~ 0.5% fractional deviation from mean.
- Cut across rows shows 27.3 pixel structure at 0.2% to 0.4%



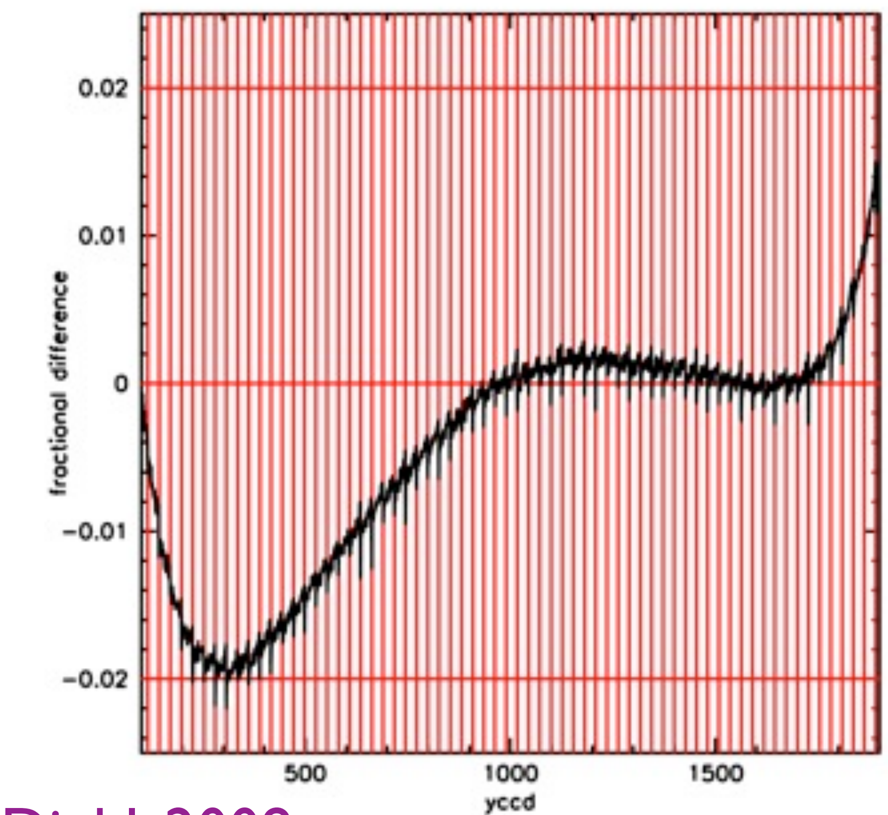


Image credit: T. Diehl, 2008

Variable Pixel Size

Small-scale Variation in Pixel Sizes

- Small scale pixel variation in the flat field is consistent with pixel sizes varying by ~0.5%.

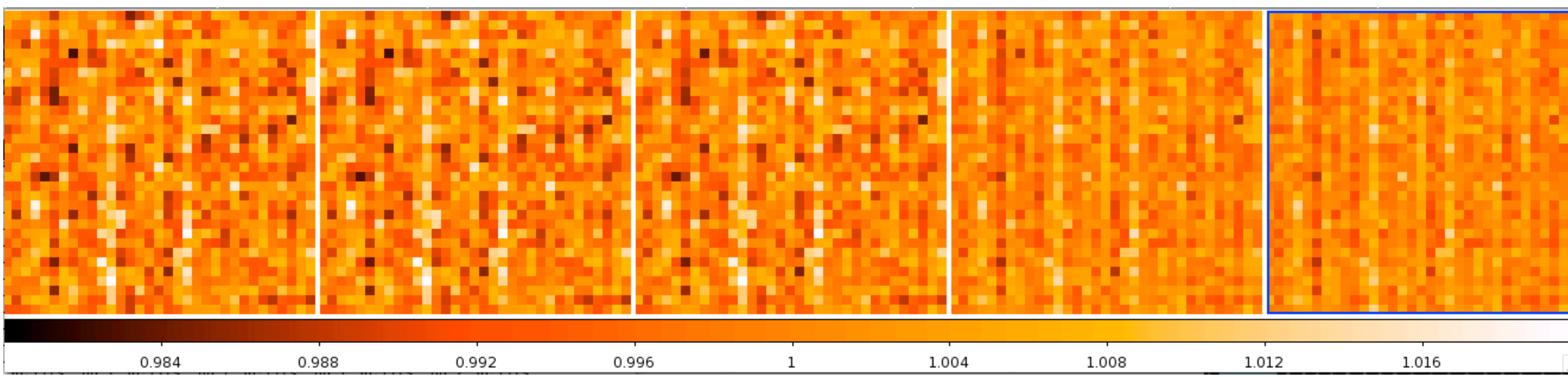


Image credit: G. Bernstein, 2013

Variable Pixel Size

- Look at the effect in one dimension for simplicity.
- Take a particular pixel that is expected to have a size s, but really has a size $s+ds$.
- The observed flux value in this pixel will be used to constrain a model intensity pattern integrated over the size of the pixel.

Variable Pixel Size

The correct treatment to first order in the Taylor expansion of *I(x)* is:

$$I_i = \int_{x_0 - (s+ds)/2}^{x_0 + (s+ds)/2} I(x)dx$$

$$\approx \int_{x_0 - (s+ds)/2}^{x_0 + (s+ds)/2} \big(I(x_0) + I'(x_0)(x - x_0) \big) dx$$

$$\approx (s + ds)I(x_0) + \frac{1}{8}(s + ds)^2 I'(x_0)$$

Variable Pixel Size

The current, incorrect treatment takes the size fluctuation as a QE fluctuation and "flattens" the flux value is:

$$I_{flattened} = \int_{x_0 - s/2}^{x_0 + s/2} I(x)dx$$

$$\frac{s}{s+ds} I_i \approx sI(x_0) + \frac{1}{8} s^2 I'(x_0)$$

$$I_i \approx (s+ds)I(x_0) + \frac{1}{8} s(s+ds)I'(x_0)$$

Variable Pixel Size

The impact on shapes:

- If $ds > 0$, then coefficient of $I'(x_0)$ is too small.
- The fit will tend to push the magnitude of $I'(x_0)$ larger to compensate, which will tighten the profile in the x direction.
- This leads to a spurious (negative) e_1 for the galaxy.
- Similarly, negative ds will lead to a spurious positive e_1.
- For variable size in the y direction, the sense of the spurious ellipticity is reversed.
- The "random" variation is probably ignorable, since these effects cancel on average, so just add to measurement noise.
- The repeating mask will lead to systematics. Need to correct this somehow.

Variable Pixel Size

Solution?:

- Just implement the correct forward model.
- Don't flatten the field. Just estimate pixel sizes.
- Integrate the model over the correct bounds for each pixel.
- This is probably too slow. Usually we include the pixel as part of the effective PSF and use FFTs for the convolution.

Variable Pixel Size

Solution?:

- Correct mean shapes post-facto. Just subtract the mean e_1 from all measured shapes.
- Will be differently wrong for each galaxy, but I think it would be ok on average.
- Assumes that this is the only source of mean e_1, which seems dangerous.
- Would get the shape correlations wrong on the scale of 8 pixels, but that's a smaller scale than we usually use for science.

Variable Pixel Size

Solution?:

- Bin e_1 galaxy shape by the x value of the central pixel (or centroid).
- Should see a functional form that repeats every 8 pixels.
- Either use the mean value for each pixel and subtract that off of the measured shapes in that bin.
- Or fit a Fourier series to the function with an 8 pixel period and use that for the actual centroid of each galaxy.
- This ignores the size of the galaxy, which is also relevant. Maybe bin in both size and centroid.

Summary

- WCS effects are relatively easy to correct **IF** we have the correct functions for the complete WCS.
  - cf. Andres Plazas's talk tomorrow!
- Bright-fatter relation is probably straightforward to correct, assuming the "tentative" model is correct.
  - c.f. Pierre Astier's talk tomorrow!
- Variable pixel sizes are tough to correct in mathematically rigorous way. Probably correct shapes post-facto, but need to try on real data.
- I ignored wavelength effects. Lots of interesting effects there to deal with as well.
  - c.f. Josh Meyers's poster!